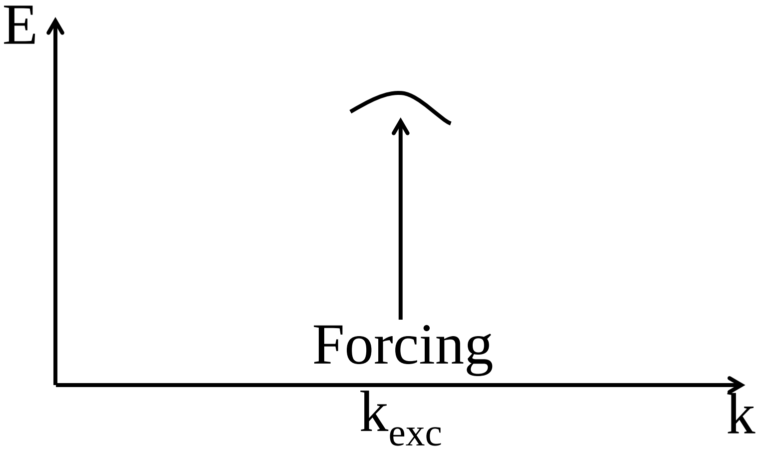
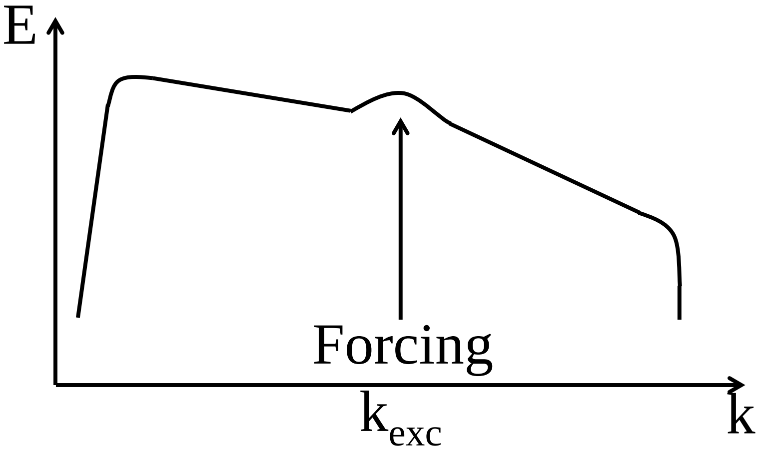
Onset of turbulence in an autooscillating complex plasma

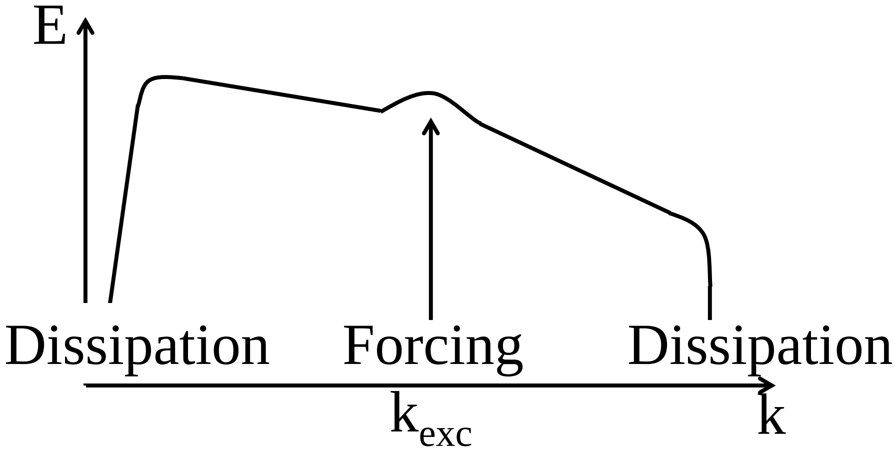
Mierk Schwabe, Sergey Zhdanov, Christoph Räth

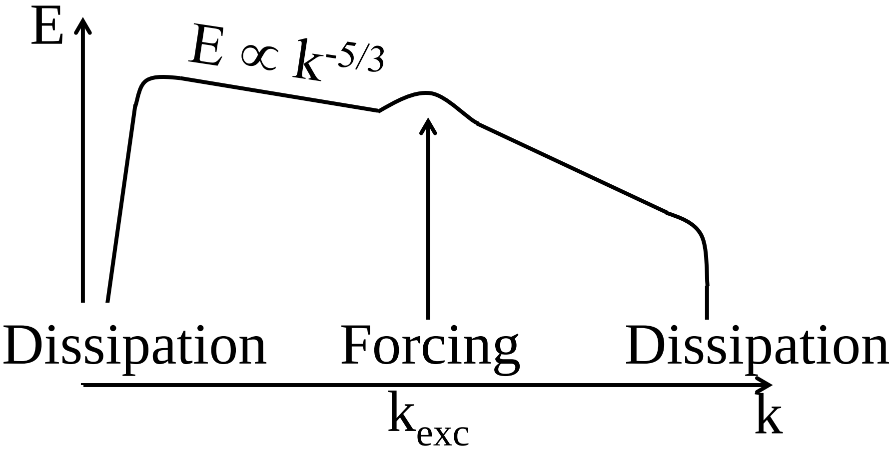
Institut für Materialphysik im Weltraum
Deutsches Zentrum für Luft- und Raumfahrt (DLR)

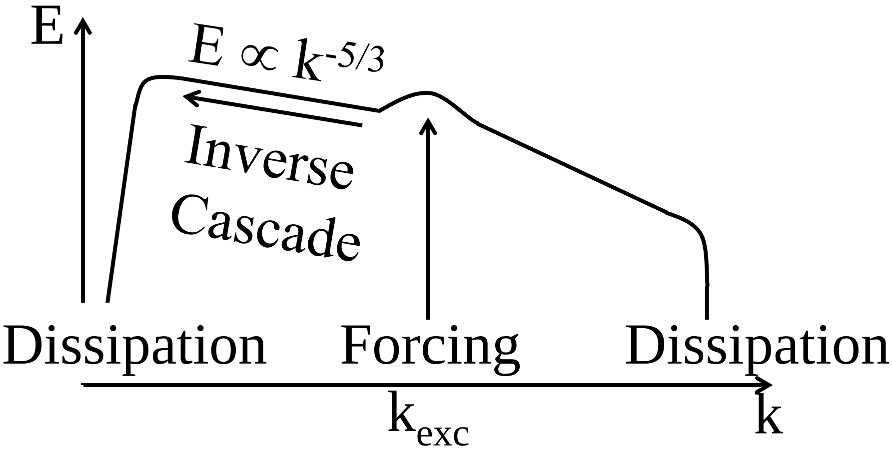

E
k

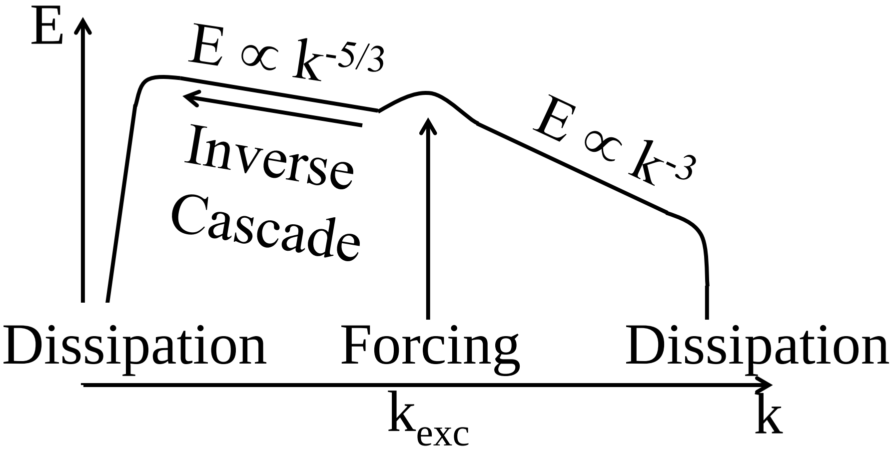

E
Forcing
k_{exc}
k


E
Forcing
k_{exc}
k

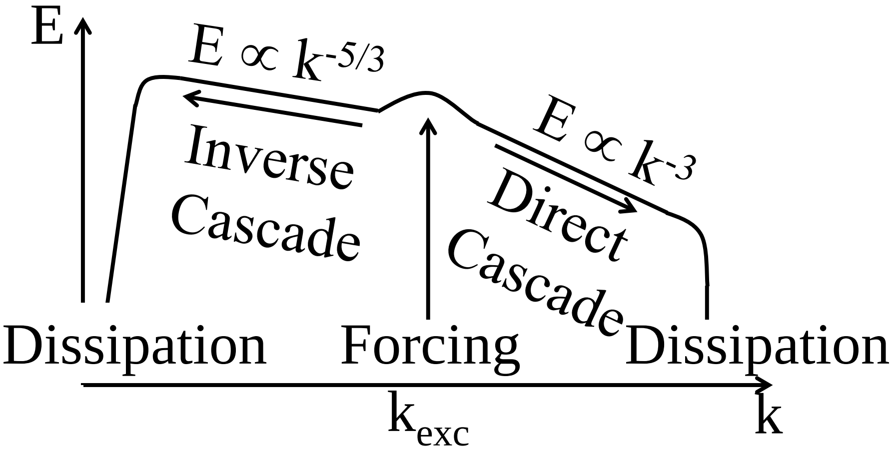

E
Dissipation
Forcing
Dissipation
k_{exc}
k

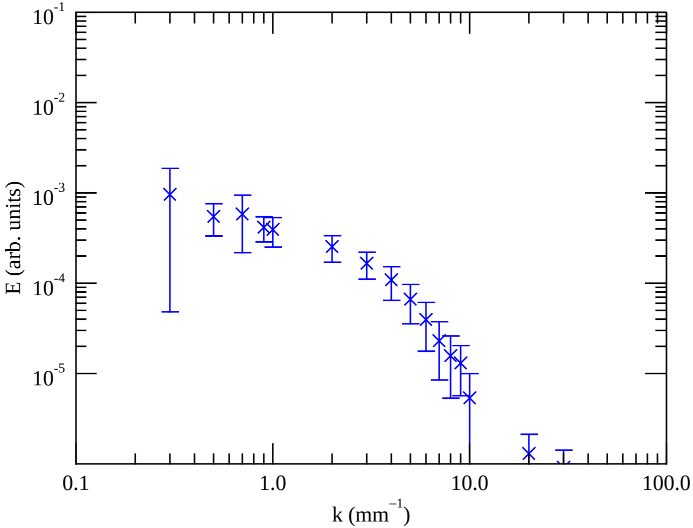

E
$E \propto k^{-5/3}$
Dissipation
Forcing
Dissipation
k_{exc}
k


E
$E \propto k^{-5/3}$
Inverse
Cascade
Dissipation
Forcing
Dissipation
k_{exc}
k

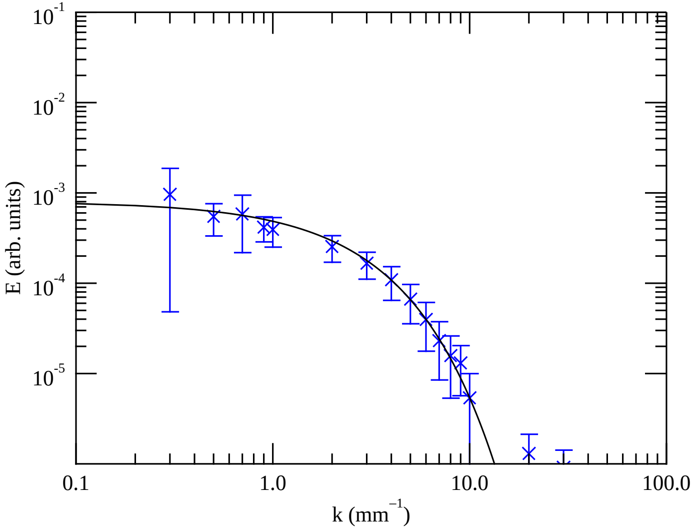


E
E ∝ k^-5/3
Inverse
Cascade
E ∝ k^-3
Dissipation
Forcing
Dissipation
k_exc
k


E
$E \propto k^{-5/3}$
Inverse
Cascade
$E \propto k^{-3}$
Direct
Cascade
Dissipation
Forcing
Dissipation
k_{exc}
k



10-1
10-2
10-3
10-4
10-5
E (arb. units)
0.1
1.0
10.0
100.0
k (mm−1)



10^-1
10^-2
10^-3
10^-4
10^-5
E (arb. units)
0.1
1.0
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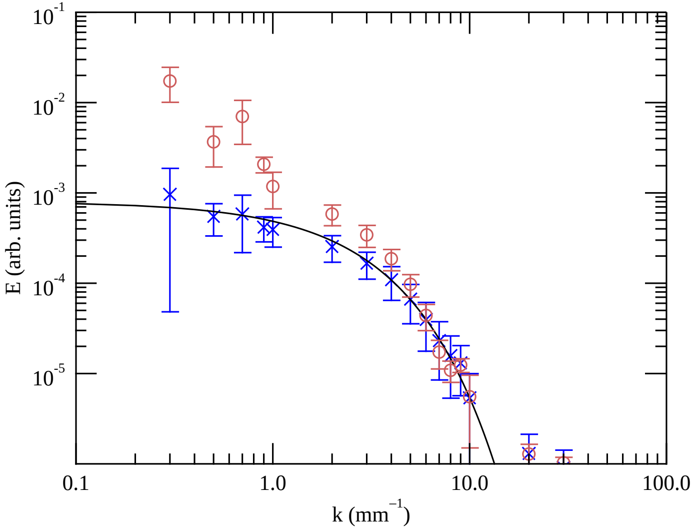
k (mm^−1)



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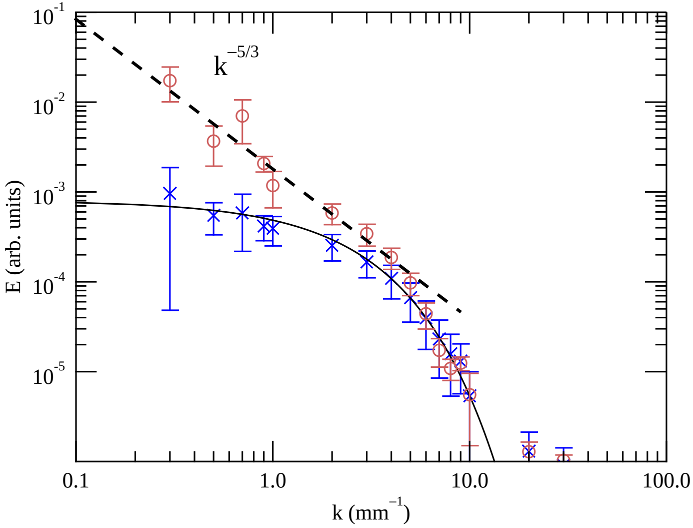
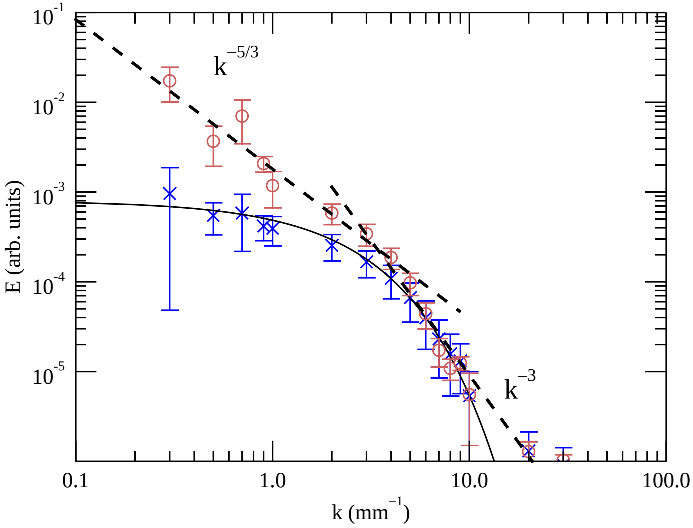
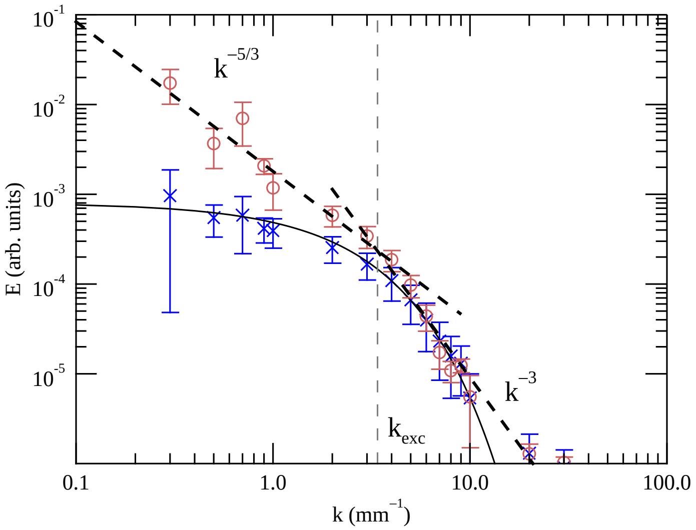


10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
E (arb. units)
$k^{-5/3}$
0.1
1.0
10.0
100.0
k (mm^{-1})



DLR



10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
E (arb. units)
$k^{-5/3}$
k^{-3}
k_{exc}
0.1
1.0
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100.0
k (mm^{-1})

Onset of turbulence in an autooscillating complex plasma

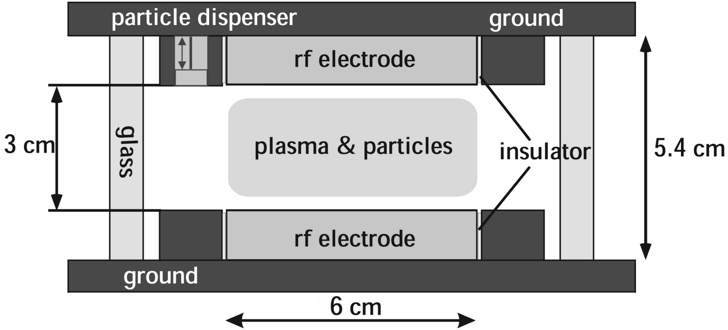
Experiment

Signature of Turbulence

Conclusion

Onset of turbulence in an autooscillating complex plasma

We performed experiments in the PK-3 Plus Laboratory on the ISS.



capacitively coupled plasma chamber

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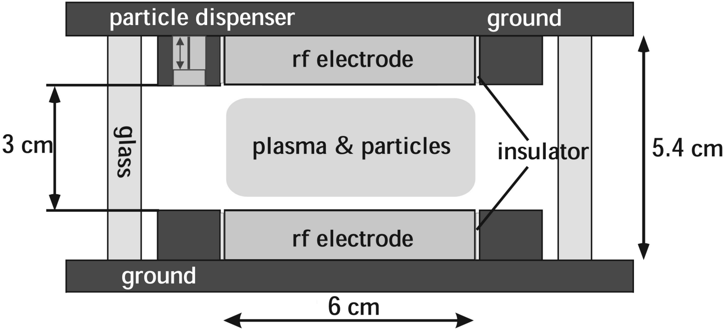

RF voltage on electrodes

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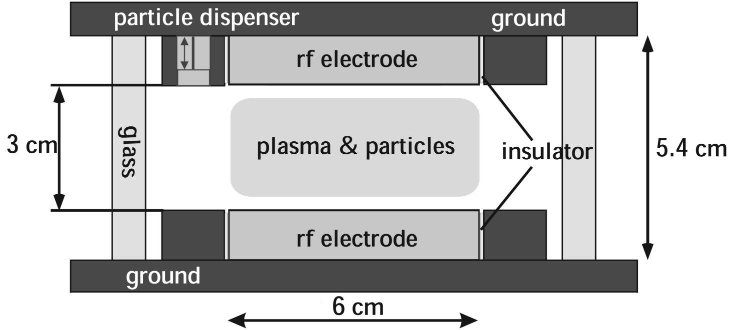

inject microparticles via dispensers

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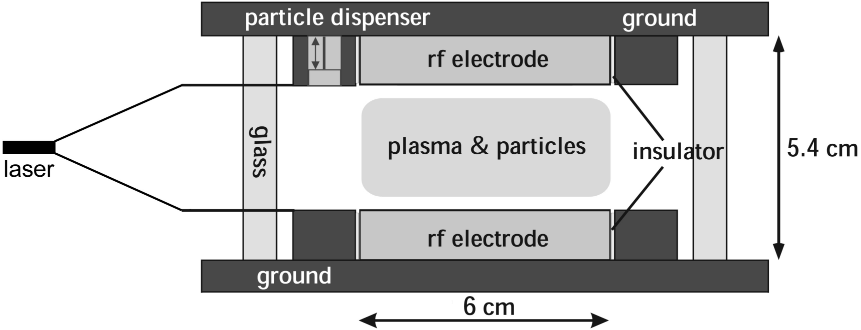
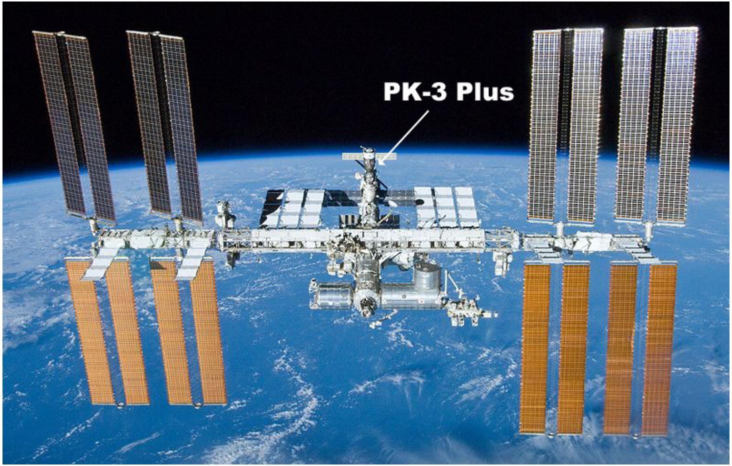


illuminate with laser from the side, trace particles

The PK-3 Plus Laboratory was hosted on the ISS from 2005 – 2014.



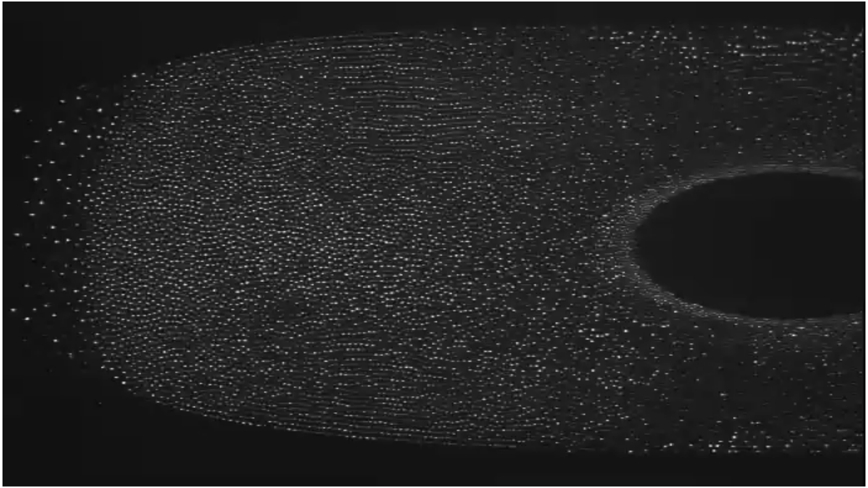
The PK-3 Plus Laboratory was hosted on the ISS from 2005 – 2014.

ISS014E05960

Image Credit: NASA/ESA

DLR

The system is often in a fluid state. Then vortices can form.



The system is often in a fluid state. Then vortices can form.

The Reynolds number in complex plasmas is very low.

$\mathcal{R} = LV/\nu \approx 4$ — L: characteristic length; V: characteristic velocity
ν: kinematic viscosity

turbulence typically occurs at very high Reynolds numbers $\mathcal{R}$

systems which are turbulent at low $\mathcal{R}$ exist, e.g. viscoelastic fluids

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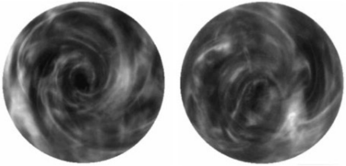
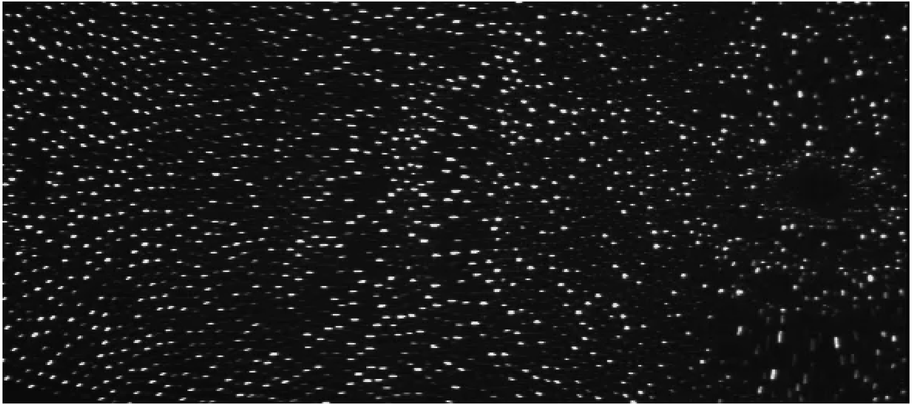


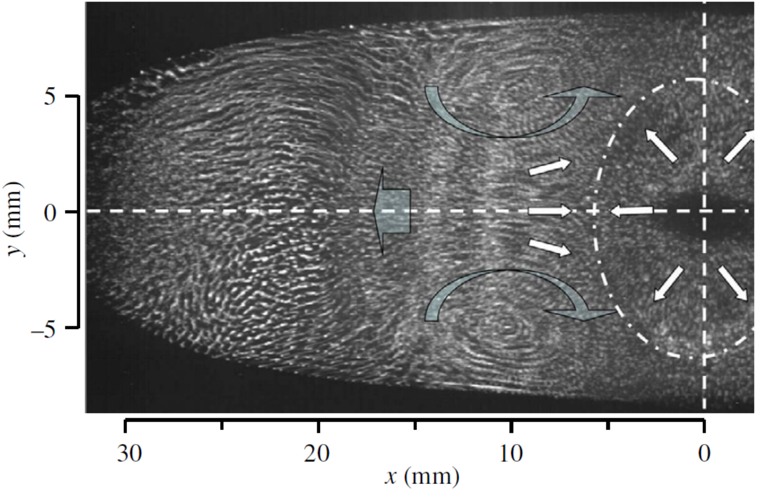
polymer solution with $\mathcal{R} = 0.7$
Groisman and Steinberg, Nature (2000)

Experimental: A heartbeat instability causes waves and oscillons.



Experimental: A heartbeat instability causes waves and oscillons.

We hypothesize that the heartbeat channels the particle flow in two dimensions.



DLR

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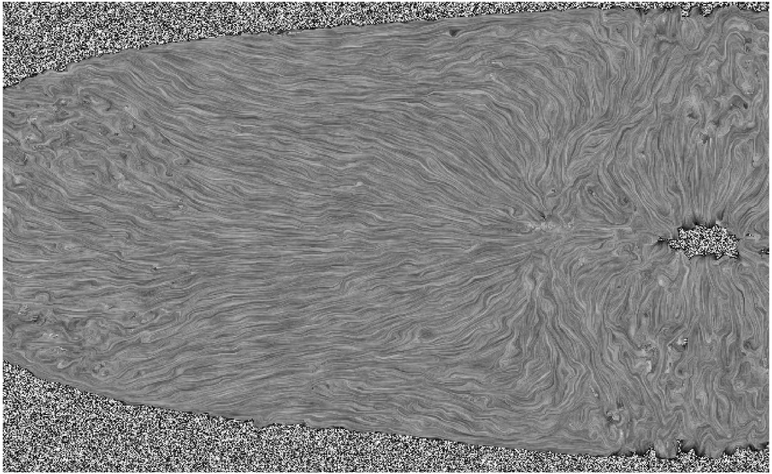
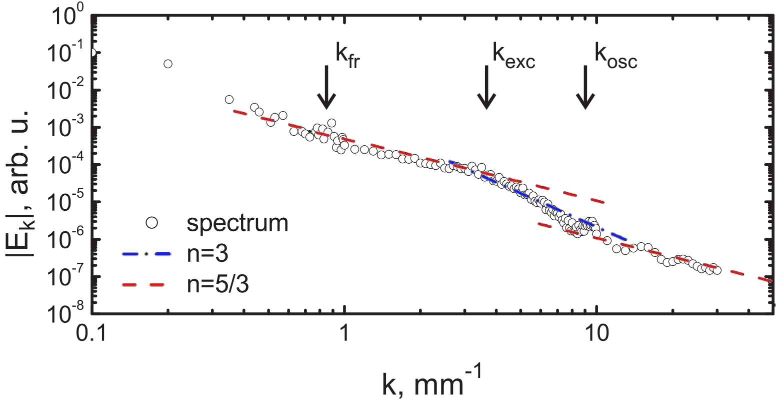
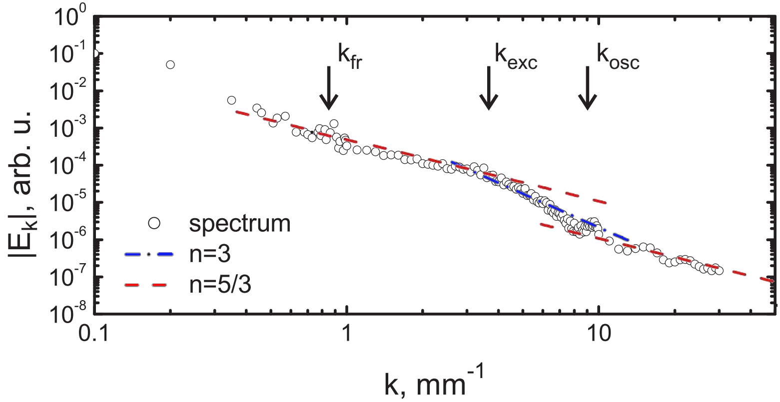


The energy spectrum is dominated by three wave numbers.



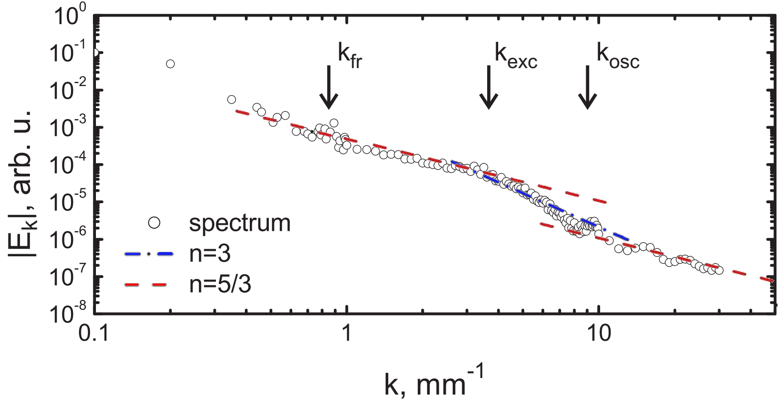
$k_{\mathrm{fr}} = \frac{\gamma_{\mathrm{damp}}}{2C_{\mathrm{DAW}}} \approx 0.84\,\mathrm{mm}^{-1}$ scale defined by friction, transition at $k < k_{\mathrm{fr}}$ to $E_{\mathrm{k}} \propto k^{-3}$ caused by friction

The energy spectrum is dominated by three wave numbers.



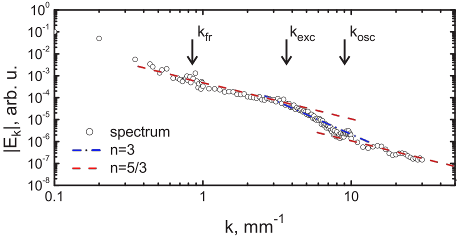
$$k_{\text{exc}} = \frac{2\pi f_{\text{HB}}}{C_{\text{DAW}}} \approx 2.7\,\text{mm}^{-1}$$ scale defined by heartbeat

The energy spectrum is dominated by three wave numbers.



$k_{osc} = \frac{2\pi}{w_{osc}} \approx 9.0\,\mathrm{mm}^{-1}$ scale defined by oscillons
modulational instability causes oscillons

The knee at k_{exc} resembles a double cascade predicted for forced 2d turbulence.



external force input at k_{exc} leads to

- inverse cascade of kinetic energy to $k \ll k_{exc}$ ($E \propto k^{-5/3}$)
- direct cascade of enstrophy to $k \gg k_{exc}$ ($E \propto k^{-3}$)

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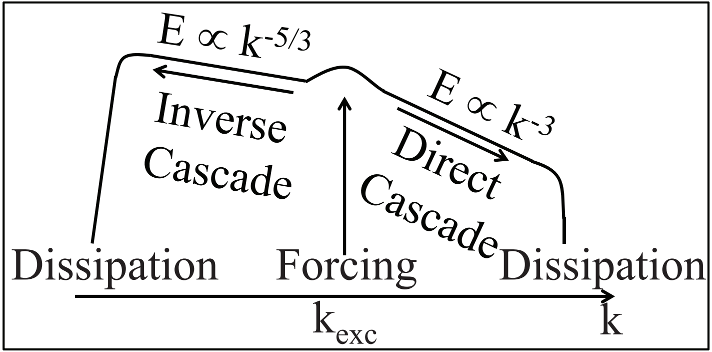
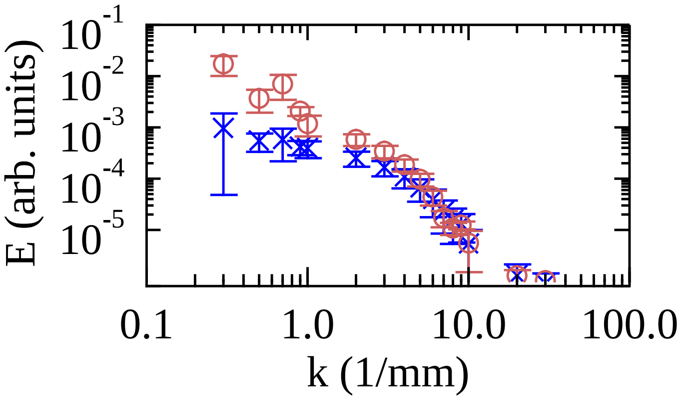
The knee at k_{exc} resembles a double cascade predicted for forced 2d turbulence.



after Laurie et al. (2012)

The energy spectrum changes dramatically with the onset of the instability.



blue crosses: before / red circles: after the onset of the instability

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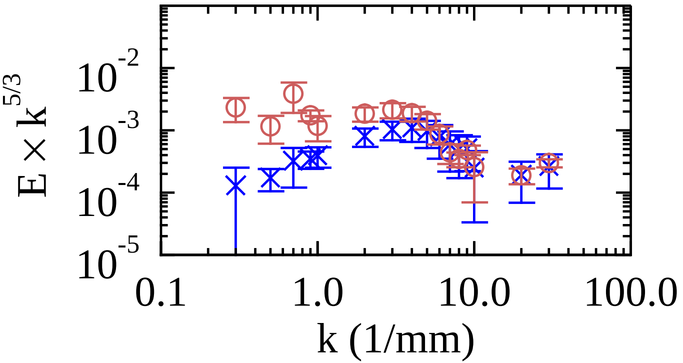

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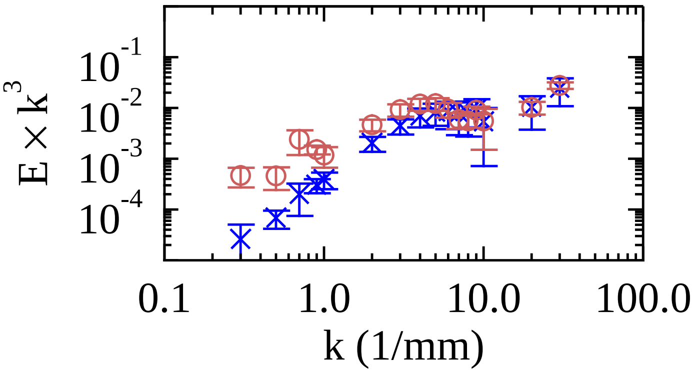

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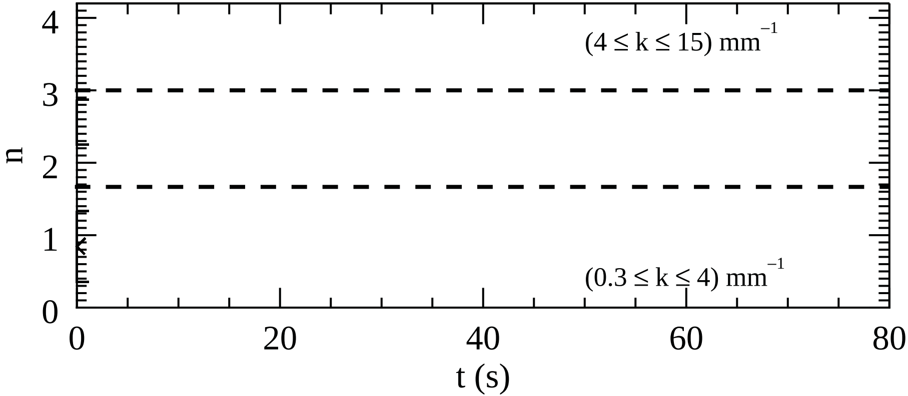
The fitted spectral exponents agree with those predicted for 2d forced turbulence.



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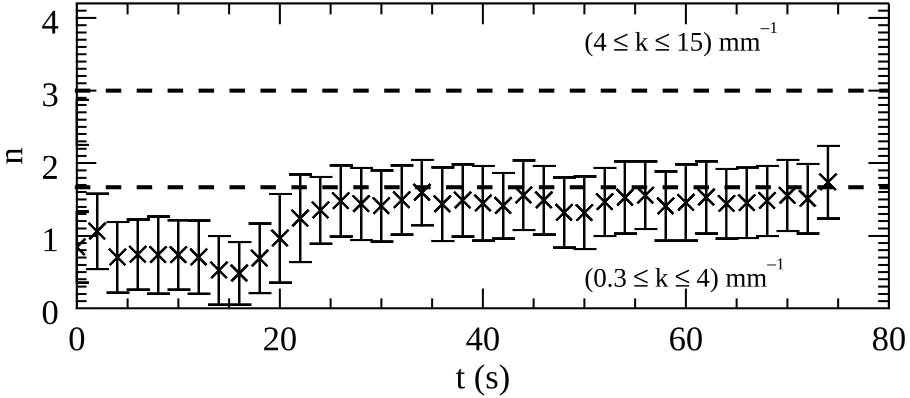

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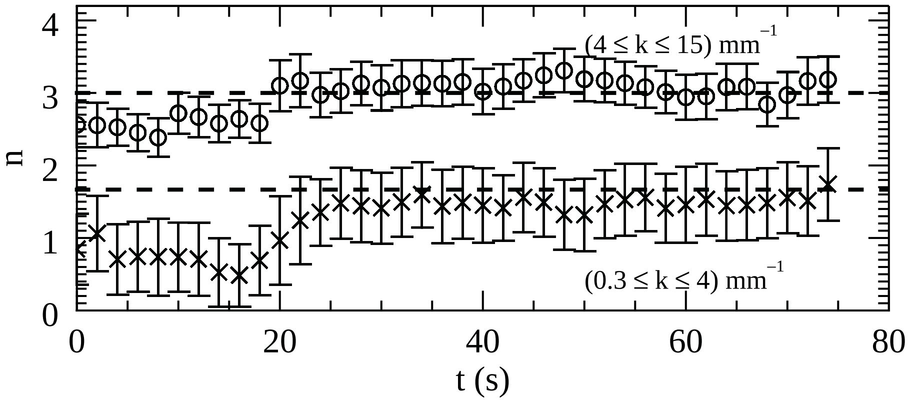


We calculate the reduced rates of energy and enstrophy transfer.

inverse cascade: $E = C\epsilon^{2/3}k^{-5/3} = \epsilon'^{2/3}k^{-5/3}$

ϵ: rate of cascade of kinetic energy / mass

direct enstrophy cascade: $E = \tilde{C}\eta^{2/3}k^{-3} = \eta'^{2/3}k^{-3}$

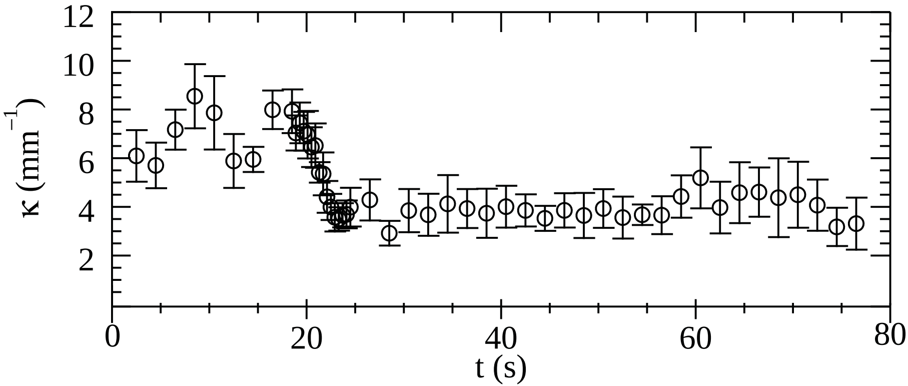
η: rate of cascade of mean-square vorticity (enstrophy)

The ratio of the reduced rates of transfer indicates the excitation wave number.

$$\kappa^2 = \eta'/\epsilon' = \left(\frac{Ek^3|_{k_2}}{Ek^{5/3}|_{k_1}} \right)^{3/2}$$

$k_1 = 2\,\text{mm}^{-1}$ – wave number in inverse cascade range
$k_2 = 6\,\text{mm}^{-1}$ – wave number in direct cascade range

The ratio of the reduced rates of transfer indicates the excitation wave number.



$\kappa = k_{\mathrm{exc}} = 3.9 \pm 0.5\,\mathrm{mm}^{-1}$

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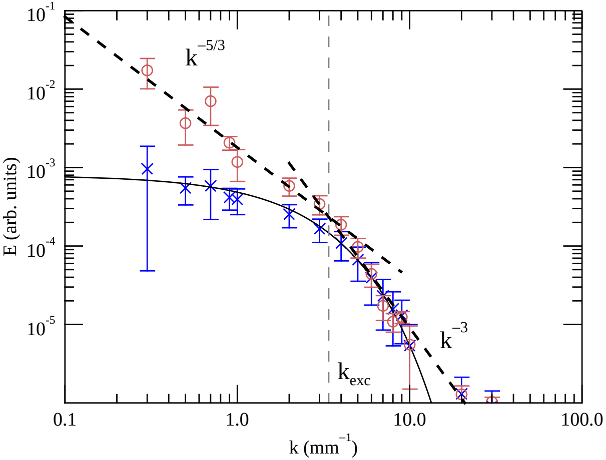
The excitation wave number determined with the reduced rates of transfer fits that where the two ranges meet.



from rates of transfer: $k_{\text{exc}} = 3.9 \pm 0.5\,\text{mm}^{-1}$

from heartbeat scale: $k_{\text{exc}} = 2.7\,\text{mm}^{-1}$

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Conclusion

- observed a double cascade in a complex plasma with heartbeat instability – not necessarily same mechanism as in 2d turbulence
- change in spectrum when instability sets in
- calculated excitation wave number
- still a lot to do! e.g., study fluxes, movement of particles, ...

Conclusion

RAPID COMMUNICATIONS

PHYSICAL REVIEW E **95**, 041201(R) (2017)

Instability onset and scaling laws of an auto-oscillating turbulent flow in a complex plasma

M. Schwabe,* S. Zhdanov, and C. Räth

Institut für Materialphysik im Weltraum, Deutsches Zentrum für Luft- und Raumfahrt (DLR), 82234 Weßling, Germany

(Received 1 September 2016; published 10 April 2017)

We study a complex plasma under microgravity conditions that is first stabilized with an oscillating electric field. Once the stabilization is stopped, the so-called heartbeat instability develops. We study how the kinetic energy spectrum changes during and after the onset of the instability and compare with the double cascade predicted by Kraichnan and Leith for two-dimensional turbulence. The onset of the instability manifests clearly in the ratio of the reduced rates of cascade of energy and enstrophy and in the power-law exponents of the energy spectra.

DOI: 10.1103/PhysRevE.95.041201

DLR

Conclusion

RAPID COMMUNICATIONS

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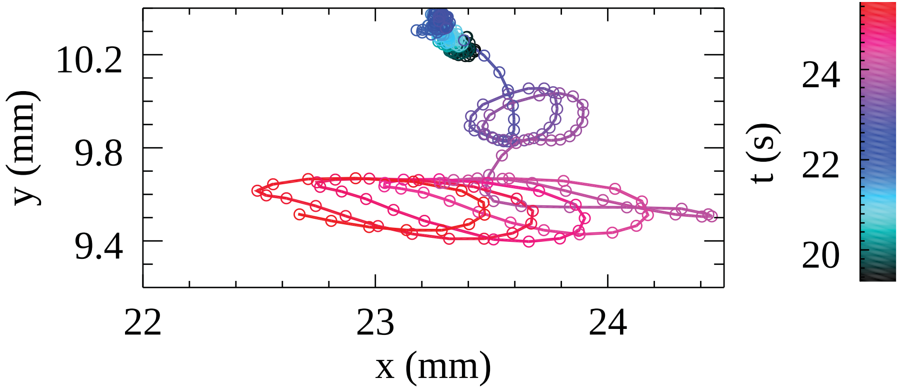
The velocity distribution changes when the heartbeat starts.



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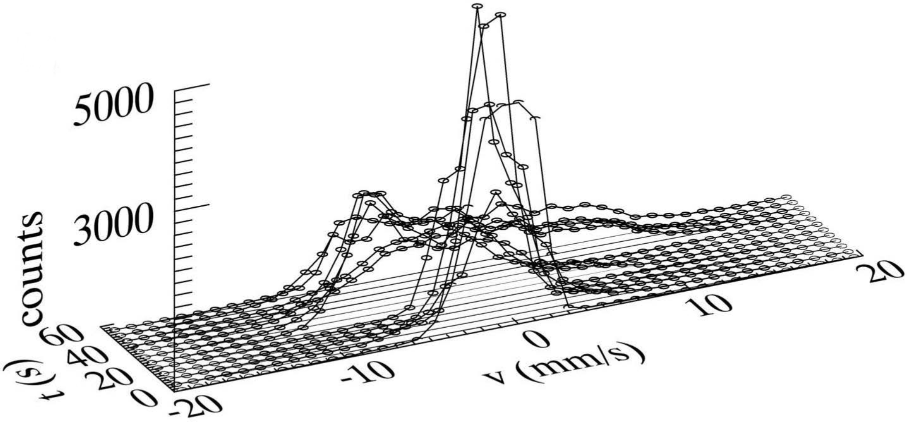

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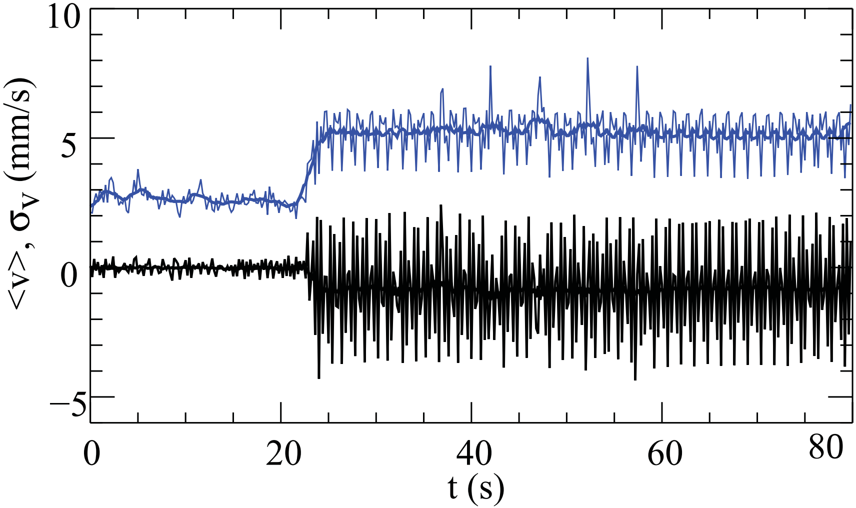

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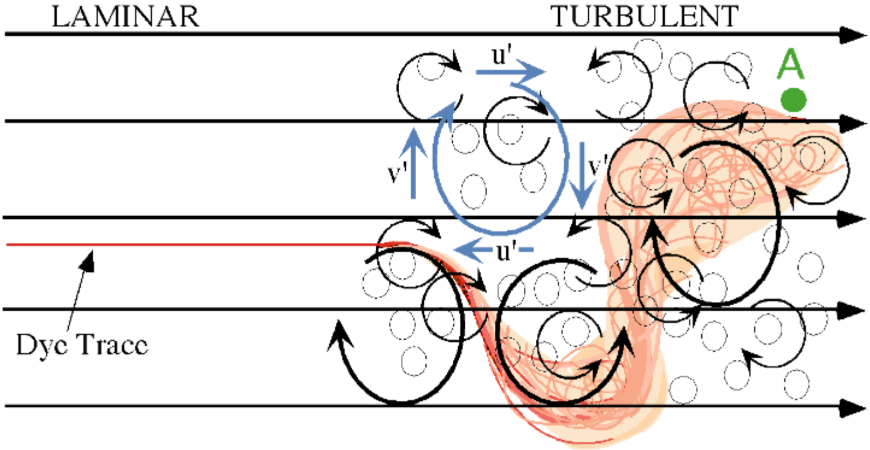
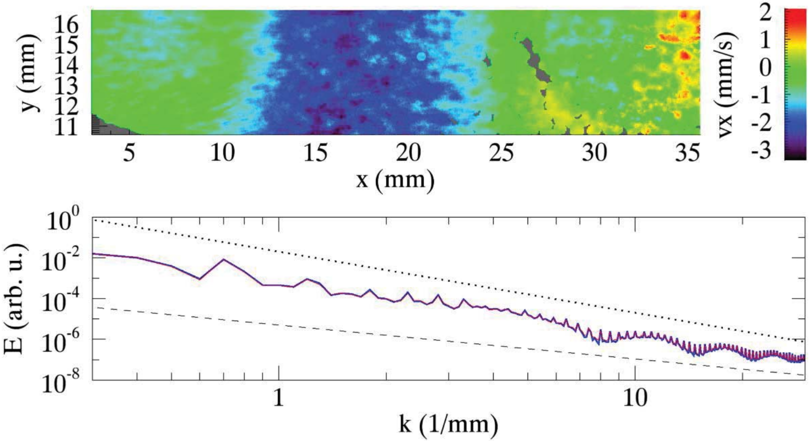
Turbulence is a superposition of movement on many scales.

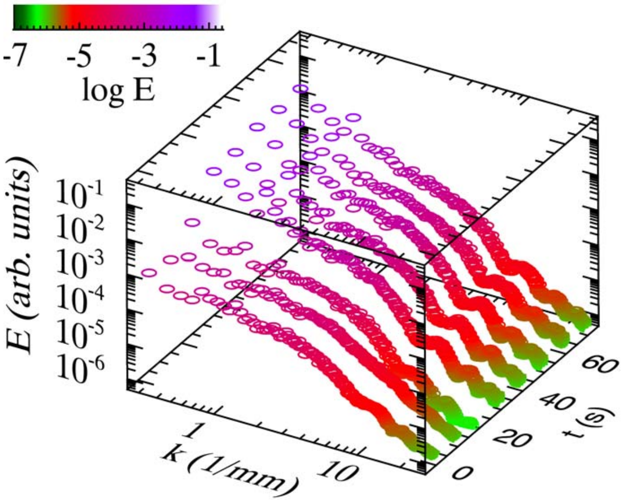


NEPF Lab, MIT

We made sure that missing data in the velocity maps did not affect the calculated spectra.



The spectra change when the instability sets in.



Enstrophy is a common quantity used in turbulence research.

$$\Omega_{kl} = \left(\frac{1}{n} \sum_{i=0}^{n} \omega_i \right)^2$$

(k, l): grid cell coordinates
$\omega_i = (\text{curl } v)_i$: vorticity
n: number of particles in cell

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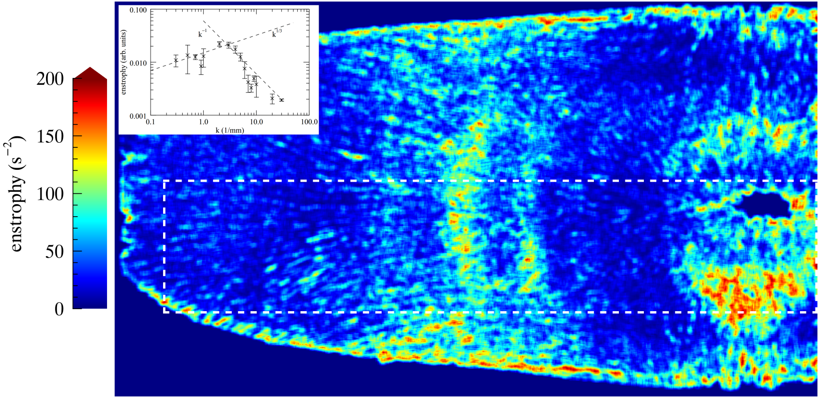
n: number of particles in cell

$\rightarrow$ potential density related to the kinetic energy that corresponds to dissipation effects in the fluid

The enstrophy spectrum also shows a similar dependence as that predicted for forced 2d turbulence.



dashed lines: power laws with the exponents -1 and -1/3